

# INTEGRAL Field Spectroscopy of the Extended Ionized Gas in Arp 220<sup>1</sup>

Luis Colina<sup>2</sup>, Santiago Arribas<sup>3,4</sup>, & David Clements<sup>5</sup>

## ABSTRACT

Integral field optical spectroscopy with the INTEGRAL system has been used to investigate for the first time the two-dimensional kinematic and ionization properties of the extended, warm ionized gas in Arp 220 over an area of  $75''.0 \times 40''.0$  (i.e.  $28 \times 15$  kpc). The structure of the ionized gas is divided into well identified regions associated with the X-ray emitting plumes and extended lobes, previously studied in detail by McDowell and collaborators. The overall ionization state of the warm gas in the plumes and lobes as traced by the  $[\text{NII}]/\text{H}\alpha$  line is consistent with high velocity shocks expanding in a neutral ambient medium. Changes in the ionization state of the gas along the major axis of the plumes are detected, in particular in the outer regions of the northwestern plume where the transition between the main stellar body of the galaxy and a broad, low surface brightness tidal tail is located. If the plumes are produced by a starburst-driven galactic wind, the efficiency in the conversion of mechanical to radiation energy is a factor of at least 10 smaller than in galactic winds developed in edge-on spirals with well defined rotation and outflowing axis. The kinematic properties of the lobes with an average velocity of  $+8 \text{ km s}^{-1}$  (E lobe) and  $-79 \text{ km s}^{-1}$  (W lobe) are to a first order in agreement with the predictions of the merger scenario according to which the lobes are tidal-induced gas condensations produced during the merging process. The largest velocity gradients of  $50 \text{ km s}^{-1} \text{ kpc}^{-1}$  and velocity deviations of up to  $+280 \text{ km s}^{-1}$  and  $-320 \text{ km s}^{-1}$  from the systemic velocity are not associated

---

<sup>1</sup>Based on observations with WHT operated on the island of La Palma by the ING in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

<sup>2</sup>Instituto de Estructura de la Materia (CSIC), Serrano 121, 28006 Madrid, Spain (colina@isis.iem.csic.es)

<sup>3</sup>Space Telescope Institute, 3700 San Martin Drive, Baltimore, USA (arribas@stsci.edu). Affiliated with the Astrophysics Division, Space Science Department of ESA.

<sup>4</sup>On leave from the Instituto de Astrofísica de Canarias – Consejo Superior de Investigaciones Científicas (CSIC)

<sup>5</sup>Physics Dept., Imperial College, Prince Consort Road, London, SW7 2BW, UK; d.clements@ic.ac.uk

with the plumes, but with the outer stellar envelope and broad tidal tails at distances of up to 7.5 kpc, indicating that the large scale kinematics of the extended ionized gas in Arp 220, is most likely dominated by the tidal-induced motions, and not by galactic winds associated with nuclear starbursts.

*Subject headings:* — galaxies: active — galaxies: nuclei — galaxies: interactions — galaxies: starburst — galaxies: individual (Arp 220)

## 1. INTRODUCTION

Arp 220 is the prototypical cool (i.e.  $f_{25}/f_{60} < 0.2$ ) Ultraluminous Infrared Galaxy (ULIRG) with an infrared luminosity  $L_{IR}(8 - 1000\mu\text{m}) = 1.45 \times 10^{12} L_{\odot}$ . Arp 220 is also the nearest ULIRG with a redshift of 0.01813, and is thus an ideal laboratory to investigate with the physical processes taken place in ULIRGs.

Arp 220 has clear signs of being at the final stage of a merging process. Optical images reveal extended, broad tidal tails (Arp 1966; Hibbard, Vacca, & Yun 2000; Surace, Sanders, & Evans 2000), and high-resolution near infrared and radio imaging show the presence of two nuclei separated by about 0.4 kpc (i.e. 0''.98 Carico et al. 1990; Graham et al. 1990; Baan & Haschick 1995; Scoville et al., 1998, 2000, and references therein). Moreover, Arp 220 is also extraordinarily rich in gas with about  $5 \times 10^9 M_{\odot}$  of molecular gas ( $M_{H_2}$ ) concentrated in the nuclear region of 250 pc in radius (Scoville, Yun & Bryant 1997).

The stellar and the cold gas components have been studied in detail (Scoville, Yun, & Bryant, 1997; Sakamoto et al., 1999; Hibbard, Vacca, & Yun, 2000; Surace, Sanders, & Evans, 2000 and references therein). The two nlr/molecular nuclei and their associated disks – which rotate in opposite directions – are embedded in a kpc scale molecular disk, and seem to rotate in the same sense as the 100 kpc scale HI disk, suggesting a prograde-retrograde encounter of two gas-rich spiral galaxies (Scoville et al. 1997).

The ionized gas component in the nuclear regions of Arp220 has been studied on the basis of long slit observations along two position angles (Heckman et al. 1990), and more recently using integral field spectroscopy with INTEGRAL (Arribas, Colina & Clements 2001, ACC01 hereafter). The detailed two-dimensional study by ACC01 has shown the complex kinematical behaviour of the ionized gas within 2 kpc from the dust-enshrouded nucleus, where three different components associated with rotation and radial flows respectively, have been identified.

The nuclear and extended X-ray emitting gas has also been investigated with ROSAT PSPC images (Heckman et al. 1996), and more recently with *CHANDRA* high spatial resolution X-ray imaging (Clements et al. 2002; McDowell et al. 2003, McD03 hereafter). The *CHANDRA* images show the presence of four distinct, spatially separated emitting regions, the hard X-ray nucleus, the circumnuclear region, the extranuclear plumes, and the extended lobes, that could be associated with different phenomena operating at different physical scales, i.e. the dust-enshrouded AGN (nucleus), the (circum-)nuclear starburst and associated winds (circumnuclear regions and plumes, respectively), and the tidal forces produced during the interaction (extended lobes).

However, a detailed kinematical and ionization study of the gas flows present in the extended ionized gas of Arp 220, and of how they are affected by the interaction process and by the massive nuclear starburst, is still lacking and requires an observational technique able to obtain two-dimensional velocity fields and ionization maps of the complex ionized gas structures detected in this galaxy over scales of about  $60''$  across. Integral field spectroscopy (IFS, e.g., Arribas & Mediavilla, 2000) is an ideal technique for such a study since it allows a simultaneous and complete mapping of both the kinematic and ionization properties of the warm ionized gas over large areas (see Arribas & Colina 2003 and references therein for previous studies of ULIRGs using integral field spectroscopy).

This paper presents the first two-dimensional spectroscopic study of the extended ionized nebula in Arp 220 covering a region of  $75'' \times 40''$ . In the following sections, the stellar morphology (§3.1), two-dimensional structure (§3.2), ionization (§3.3), and kinematics (§3.4) of the ionized gas are presented. The origin of the extended ionized gas as produced by starburst-driven galactic winds (§ 4.1), and tidal forces during the merger process (§ 4.2) are briefly discussed. Throughout the paper, a distance of 77.6 Mpc. At the assumed distance,  $1''$  corresponds to 375 pc.

## 2. OBSERVATIONS AND DATA REDUCTION

Integral field spectroscopy of Arp 220 was obtained with the INTEGRAL system (Arribas et al. 1998) and the WYFFOS spectrograph (Bingham et al. 1994) in the 4.2m William Herschel Telescope. We used the wide field observing mode (i.e. bundle of fibers SB3), which consists of 115 fibers, each of  $2.7''$  in diameter, and covering a  $33.6'' \times 29.4''$  field-of-view. In addition, 20 fibers distributed in a circle of  $45''$  in radius were used for simultaneous sky measurements. The spectra were taken using a 600 line/mm grating with an effective resolution of about  $9.8 \text{ \AA}$  and covering the  $4500\text{--}7500 \text{ \AA}$  spectral range. The observations consisted of a mosaic of three pointings (nuclear, east and west nebula)

covering almost completely a rectangular area of  $75'' \times 40''$  (see Figure 1). The total integration time in each of the pointings, split into separated integrations of 1500 sec each, was 6000 sec. for the nucleus, 15000 sec. for the east nebula, and 18000 sec. for the west nebula. The seeing ( $1''.1$  -  $1''.2$ ) was very stable over the entire observing period (two nights) and conditions were spectrophotometric.

Data reduction followed the standard procedures applied to spectra obtained with two-dimensional fiber spectrographs that have been explained elsewhere (Arribas et al. 1997, and references therein; see also ACC01). The 2D distribution of the reduced spectra in the range of the redshifted  $H\alpha$  and [NII] lines are presented in Figure 2. The changes in the profiles of the lines and in the ionization conditions (i.e. [NII]/ $H\alpha$  ratio) are obvious even from this figure alone.

The absolute calibration was obtained observing the standard star SP1550+330 with the same system configuration and data reduction procedures as used for Arp 220. The relative calibration of the different pointings agrees to within 20%, as obtained by comparing the regions of overlapping. Taking into account additional uncertainties like the reliability of the  $H\alpha$  and [NII] lines fits, the uncertainty in the absolute calibration is about 30%.

### 3. RESULTS

#### 3.1. Stellar Structure

The reduced two-dimensional spectra can be used to generate continuum and emission line images by selecting specific wavelength windows. A red, narrow band (7425-7455 Å) continuum image (Figure 3) is generated for a direct comparison with the archival HST/WFPC2 I-band (F814W filter; P.I. K. Borne) image of Arp 220 (Figure 1). Although with a poorer spatial resolution, the INTEGRAL red continuum image shows an overall stellar morphology in the nuclear regions similar to the structure detected in the WFPC2 I-band image. In particular the nuclear dust lane that cuts the stellar distribution in half is clearly visible, with the apparent optical nucleus, identified as the continuum peak at these wavelengths, located northwest of it. The position of this peak, that corresponds to  $\alpha(1950) = 15^{\text{h}} 32^{\text{m}} 46.8^{\text{s}}$  and  $\delta(1950) = 23^{\circ} 41' 09''.3$  with an uncertainty of  $1''.0$  is offset from the infrared and radio nucleus by  $1''.5$ – $2''.0$  (see ACC01).

An additional feature worth mentioning is the disrupted stellar light distribution in the outer regions at distances between 4 and 11 kpc, i.e.  $10''.0$  to  $30''.0$ , from the nucleus (see Figure 3). These regions correspond most likely to tidal tails and external regions of the stellar disks in the progenitor galaxies involved in the merger. The faint northwestern tail

detected in the WFPC2 image (Figure 1) is clearly identified in the low resolution INTEGRAL continuum image (Figure 3) as a broad structure centered at about  $20''0$  (i.e. 7.5 kpc) northwest of the nucleus and elongated almost parallel to the dust lane orientation for about 7 kpc. On the eastern side, the stellar envelope extends towards the SE up to a distance of about  $30''0$  (i.e. 11 kpc). While the major axis of the nuclear stellar light distribution is given by the central dust lane along position angle PA  $45 (\pm 5)$ , the extended stellar envelope, as seen also in the WFPC2 image and in previous deep ground-based images (Hibbard, Vacca & Yun 2000), has a major axis oriented along PA  $110$ , away from that of the dust lane and almost perpendicular to it. All these characteristics point to a stellar system in Arp 220 that as a consequence of the merging process, has not yet reached its dynamically relaxed configuration.

### 3.2. Extended Ionized Gas: Structure

The major axis of the diffuse, optical ionized gas in Arp 220 has an end-to-end size of 24 kpc, similar in length to the extended soft X-ray emitting regions (Heckman et al. 1996; McD03). The ionized gas distribution traced by the  $H\alpha$  (Figure 4a) and  $[NII] 6584\text{\AA}$  (Figure 4b) emission lines clearly shows substructures and different components at various linear scales. As originally noted by Heckman et al. (1996), and recently confirmed with higher spatial resolution *CHANDRA* images (McD03), the structure of the extended X-ray emission bears a strong morphological resemblance to the warm ionized gas traced by the optical emission lines. For consistency with the different components of the X-ray emitting gas already identified, we will also refer in the rest of the paper to the circumnuclear regions, plumes and lobes, to identify the optical ionized gas regions at various scales. A summary of several observed and derived properties for the different regions is given in Table 1.

#### 3.2.1. The Nucleus and Circumnuclear Region

The nucleus and its surrounding circumnuclear region up to a radius of 2 kpc have already been investigated in more detail using INTEGRAL with a higher spatial and spectral resolution configuration (see ACC01 for details). The  $H\alpha$  emission peaks at  $0''8$  (i.e. 0.3 kpc) southwest of the optical stellar continuum peak, and coincides with the position of the soft X-ray emission peak, which is displaced  $1''5$  northwest of the hard X-ray emission source (Clements et al. 2002). The hard X-ray source agrees in position with the mid-infrared and brightest radio source (Soifer et al. 2000), and it is consequently

considered as the true nucleus of Arp 220. Therefore, the warm  $H\alpha$  ionized gas associated with the nuclear hard X-ray source is enshrouded by the nuclear dust lane and appears distributed with an apparent emission peak displaced 0.6 kpc northwest of the true ionizing nucleus.

### 3.2.2. *The Plumes*

On a scale of a few kiloparsecs, and up to distances of 4 kpc from the nucleus, two elongated high surface brightness regions, one on each side of the nucleus, with a total length of 7 kpc are identified. These regions, oriented along a position angle of 120 to 140 degrees coincide with the X-ray emitting NW and SE plumes (McD03). As for the soft X-ray emission, the surface brightness of the outer part of the SE plume, not affected by the absorption due to the central dust lane, is a factor four that of the NW plume (Figures 4a, 4b) indicating a clear intrinsic asymmetry in the properties of the warm and hot ionized gas in opposite directions of the dust-enshrouded nucleus. The close similarity of the  $[NII]+H\alpha$  and the X-ray plumes in relative surface brightness (i.e. the SE plume is brighter than the NW plume by the same factor in both  $H\alpha$  and X-ray emission), and morphology (see Figure 9 in McD03) indicates that the warm and hot ionized gas components are closely related, and most likely have the same physical origin (see §4 for further discussion).

As mentioned above, the line emitting gas in the SE plume has on average a surface brightness four times that of the NW plume. There are several mechanisms that can be invoked to explain this asymmetry but none of them is clearly supported by the present set of data. Assuming the same geometry for both sides of the plume and that they are viewing the same radiation field coming from the nucleus, this enhancement in brightness could be explained by a density effect. Since  $H\alpha$  and  $[NII]$  emission are a function of  $N_e^2$ , a difference of four in surface brightness would imply a difference of two in density, and therefore the gas in the SE plume would be a factor two more dense than the corresponding gas in the NW plume. However, there is no clear evidence for this systematic difference in the electron density of the ionized gas. The measured  $[SII]$  6717Å to 6731Å emission line ratio gives values of the order of 1.0 – 1.1, consistent with an average density of a few hundred particles per unit of volume in both SE and NW plumes. An alternative explanation could be that the NW plume is seen through the dust lane, the intrinsic emission more absorbed, and consequently the surface brightness diminished relative to that of the SE plume. Although the non detection of the  $H\beta$  line in emission precludes any quantitative estimate of the local extinction using the Balmer decrement, this scenario seems also not to be valid since there is no evidence for a radial

dependency of the NW to SE plume’s relative surface brightness. In addition a factor four in absorption would imply an almost constant extinction equivalent to 3 mag. in the visual over distances of several kpc, which seems very unlikely in view of the non uniform structure of the dust lane which also runs almost perpendicular to the orientation of the plumes. A likely explanation for the difference in surface brightness is that the radiation field seen by the gas in the plumes, i.e. at distances of few to several kpc, is not symmetric with respect to the nucleus. This could be the case if the three dimensional structure of the dense dust and gas in the nuclear regions surrounding the dust-enshrouded nucleus were such that would block the radiation preferentially along a given direction.

At a lower surface brightness, there is a secondary plume (or filament) located south of the NW plume, and elongated mostly parallel to it from  $(-5''.0, -4''.0)$  to  $(-12''.0, +8''.0)$ , with a total length of about  $10''.0$  (i.e. 3.75 kpc). The southwestern part of this secondary plume, brightest in [NII] light, emerges from the main circumnuclear emission peak (see Figure 4b) while the northwestern part of it, traced by the  $H\alpha$  line, curves at  $(-10''.0, +1''.0)$  to reconnect with the NW plume at its tip (see Figure 4a).

### 3.2.3. *The Lobes*

On scales of several kiloparsecs, at distances between 4 to 15 kpc from the nucleus, the  $H\alpha$  and [NII] light distributions show the presence of two extended, limb-brightened lobes, one on each side of the nucleus. The west lobe (W lobe hereafter) is about a factor two brighter than the east lobe (E lobe hereafter), and has an edge-brightened structure with a diameter of about 4.5 kpc centered at 7 kpc west of the nucleus. On the other hand, the low surface brightness E lobe centered at 9.4 kpc from the nucleus, is actually located southeast of the nucleus, and has an ellipsoidal edge-brightened shape with a major axis of about 9 kpc oriented along a position angle of 90 degrees (Figure 4b).

An additional important feature is that the ionized gas in the lobes tend to avoid the regions occupied by the extended stellar envelope in the SE and by the broad tidal tails detected in the NW (see Figures 3 and 4b). Moreover, the optical lobes also avoid the neutral HI gas distribution that is located at about the same radial distances from the nucleus but at a position angle of 50 degrees (Hibbard, Vacca & Yun 2000). On the contrary, as already known from previous studies (Heckman et al. 1996; McD03), the overall structure of the optical lobes coincides with the X-ray lobes. This spatial segregation between, on one side the warm and hot gas, and on the other side the stellar and the cold neutral gas could favor the idea that the observed stellar and gas distributions in the outer regions of a merger system like Arp 220 are the result of the tidal forces

induced during the merging process. Therefore, the structure and energetic of the ionized gas in these lobes are not associated with a starburst generated wind but with the tidal forces and evolutionary state of the merger (see §4.2 and McD03 for further discussions).

### 3.3. Extended Ionized Gas: The Ionization State

#### 3.3.1. *The Nucleus and Circumnuclear Region*

The ionization state of the circumnuclear region has been studied in more detail in ACC01. However, the main results are briefly summarized here in order to get a complete picture of the ionization of the gas at different scales. Due to the absorption caused by the dust lane, the nucleus itself, identified as the hard X-ray, infrared and radio emission peak, is not detected as the brightest region in emission lines. As already mentioned, the peak of the  $H\alpha$  and [NII] emission line distributions is located at about  $1''.5$  NW (0.6 kpc) of the dust-enshrouded nucleus. The ionization structure of the warm gas in the circumnuclear regions is very homogeneous with a few well-localized regions where a change in the ionization state is detected (ACC01). On average, the overall ionization is consistent with LINER-like emission, or even Seyfert 2 around the peak ionized gas emission, if the lower limits to the [OIII]/ $H\beta$  and [OI]/ $H\alpha$  ratios are considered (see ACC01 for further details).

#### 3.3.2. *The Plumes*

The ionization state of the plumes presents a complex structure with well-identified regions along their major axis where the excitation conditions change on the scale of kpc. The circumnuclear  $H\alpha$  and [NII] main emission peaks located northwest of the dust-enshrouded nucleus are spatially coincident. However, the  $H\alpha$  and [NII] secondary emission peaks are offset by about 1 to 1.4 kpc, and present a clear pattern. The [NII] secondary peaks in the SE and NW plumes are located at distances of about 2 to 2.6 kpc from the main emission peak, respectively. On the other hand, the  $H\alpha$  secondary peaks are located at the tips of the plumes, at distances of about 3.5 kpc. The average ionization state of the gas in the plumes is characterized by a [NII]/ $H\alpha$  ratio of the order of 1.4 to 2.0, presenting a maximum value of 3 in the region identified as the [NII] emission peak in the NW plume. Similarly, the [SII]/ $H\alpha$  ratios have values of about 1, with a slightly larger value in the region of the [NII] emission peak. Values this large for the [NII] and [SII] emission lines with respect to  $H\alpha$  are consistent with high velocity shocks ( $\sim 300 \text{ km s}^{-1}$ ) expanding in a neutral, not preionized, medium (Dopita & Sutherland 1995).



The ionization state in the secondary plume/filament, south of the NW plume (see §3.2.2 for details on its orientation and length), also presents very interesting features. Ionization gradients are clearly visible in this plume as traced by the regions of  $H\alpha$  and [NII] high surface brightness. While the southwestern region of the secondary plume, emerging from the main line emitting peak, emits mostly in [NII] light, the  $H\alpha$  emission takes over in the curved northwestern region that reconnects this secondary plume with the tip of the NW plume (see Figures 4a and 4b). The change in the ionization, in particular the enhancement of  $H\alpha$  with respect to [NII] appears in a region where an abrupt change in the velocity of the gas by about  $50\text{--}60 \text{ km s}^{-1} \text{ kpc}^{-1}$  is detected (see §3.4.2 and Figures 5a and 5b).

### 3.3.3. *The Lobes*

The ionized gas in the extended lobes is asymmetrically distributed with the W lobe being on average a factor four brighter than the E lobe. The ionization state as traced by the [NII]/ $H\alpha$  ratio (1.1 to 1.4) is very uniform over the entire extension of the lobes, without any indications of ionization gradients or substructures at the present resolution ( $3''$ , or about 1.1 kpc). As for the plumes, the detection of strong [NII] emission with respect to  $H\alpha$  ([NII]/ $H\alpha$  ratio between 1.1 and 1.4) is consistent with high velocity shocks evolving in a neutral, not pre-ionized, medium, although additional measurements of the [OIII]/ $H\beta$  ratio would be needed to confirm this (see Dopita & Sutherland 1995). The average density of the ionized gas in the W lobe is lower than in the plumes, and less than 100 electrons per  $\text{cm}^{-3}$  as measured by the [SII] lines ratio. The weakness of the [SII] line emission in the SE lobe, precludes any measurement of the density in this region.

## 3.4. Extended Ionized Gas: Velocity Field

The large scale velocity field over the entire region of about  $75''0 \times 40''0$  has been traced by the [NII] 6584Å emission line (see Figure 5). The velocity field is rather complex, without any regular pattern but with substructures and large velocity gradients already visible on scales of 1–1.5 kpc that can be associated with different structures identified in the stellar and gas components. The systemic velocity ( $cz$ ) of Arp 220 defined as the velocity of the gas located in the region of the dust-enshrouded nucleus is  $5400 \pm 20 \text{ km s}^{-1}$  (ACC01). The velocities mentioned in the following sections will be given relative to this value.

### 3.4.1. *The Nucleus and Circumnuclear Region*

The velocity field in this region shows a very complex behaviour characterized by the presence of at least three kinematically and spatially separated components associated with rotation and radial flows. A detailed investigation of the gas motions in these regions can be found in ACC01.

### 3.4.2. *The Plumes*

The velocity field of the SE and NW plumes show a very different structure. The NW plume shows a smooth velocity field with an average approaching velocity of  $-102 \pm 37$  km s<sup>-1</sup>, and a very small velocity gradient of less than 5 km s<sup>-1</sup> kpc<sup>-1</sup>. On the contrary, the SE plume has an average velocity of  $-4 \pm 63$  km s<sup>-1</sup>, i.e. consistent with the systemic velocity, but it presents large velocity gradients. In particular, while the inner parts of the SE plume, i.e. closer to the dust-enshrouded nucleus, show a velocity similar to systemic, the outer regions identified by the tip of the [NII] emission, and by the local H $\alpha$  emission peak, show velocity changes from about systemic, or even approaching, up to  $+100 - 120$  km s<sup>-1</sup>, implying velocity gradients of about 70 to 100 km s<sup>-1</sup> kpc<sup>-1</sup>.

The velocity structure of the secondary plume/filament is such that the gas is moving with a velocity of  $-25$  km s<sup>-1</sup> in the southwestern region connecting with the [NII] and H $\alpha$  main emission peak, increases up to  $+85$  km s<sup>-1</sup> at 10''0 NW of the emission peak, and decreases again to about  $-50$  km s<sup>-1</sup> in the region where this filament reconnects with the tip of the NW plume, where an approaching velocity of  $-115$  km s<sup>-1</sup> has been measured.

It is difficult to explain the very different kinematic behaviour observed in the plumes under the simple scenario of a symmetric biconical outflow having a common origin in the dust-enshrouded nucleus. Differences in the physical conditions and/or kinematics of the interstellar medium, interactions between several gas systems moving with large relative velocities, and/or different relative orientations of the outflowing axis in the plumes have to be invoked before reaching any conclusion about the origin and evolution of the plumes (see discussion in §4).

### 3.4.3. *The Lobes*

The velocity field of the ionized gas in the lobes indicates that the W lobe is approaching with an average velocity of  $-79 \pm 58$  km s<sup>-1</sup> while the E lobe has a velocity of  $+8 \pm 79$

$\text{km s}^{-1}$ , consistent with the velocity of the system. Therefore, the average velocity of the lobes is consistent, although with a larger dispersion, with that of their corresponding plumes, independent of the overall physical scale of the two structures and of the different orientations of their major axis. The W lobe has a velocity field with a maximum receding velocity of  $+30 \text{ km s}^{-1}$  and a minimum approaching velocity of about  $-160 \text{ km s}^{-1}$  at  $25''.0$  (i.e.  $9.4 \text{ kpc}$ ) east of nucleus. The southern section of this lobe has approaching velocities of up to  $-70 \text{ km s}^{-1}$ . The ionized gas in the E lobe has also approaching velocities in the  $-25 \text{ km s}^{-1}$  to  $-60 \text{ km s}^{-1}$  range with a maximum velocity of only  $+10 \text{ km s}^{-1}$ , consistent with the systemic velocity.

Other important aspect of the ionized gas located in the limb-brightened lobes is its different kinematical behaviour with respect to the corresponding gas associated, at least in projection, with the southeastern stellar envelope and the broad, northwestern tidal tail. This velocity difference amounts to  $+75 \text{ km s}^{-1}$  and  $+190 \text{ km s}^{-1}$  for the gas in the E and W lobes, respectively (see §3.4.4). These large velocity difference suggest that the relatively high surface brightness lobes are physically separated and kinematically distinct from the low surface brightness, merger-induced stellar envelope and tidal tail (see §4.2 for a more detailed discussion).

#### 3.4.4. *Diffuse Gas Associated with the Stellar Envelope and Tidal Tail*

In addition to the ionized gas associated with the X-ray emitting plumes and lobes, there are low surface brightness ionized gas regions that seem to be associated with stellar structures that have been produced by the tidal forces generated during the evolution of the merger. These regions, as already mentioned, are identified as the extended stellar envelope southeast of the nucleus, and as the broad, low surface brightness tidal tail northwest of the nucleus.

Although the ionized gas in these regions represents a minor contribution to the overall content, both in mass and energy, the largest deviations from systemic velocity are detected in these low surface brightness regions, and the velocity substructure of this diffuse gas follows precisely the changes detected in the structure of the stellar light distribution (see Figure 5c). The gas in the southwestern side of the central dust lane moves with velocities of  $-110 \text{ km s}^{-1}$ . Moreover, the gas associated with the broad stellar tidal tail located at about  $20''.0$  W of nucleus is moving with an approaching velocity of up to  $-320 \text{ km s}^{-1}$ , representing the absolute minimum of the overall velocity field. On the other hand, low surface brightness gas associated with the southeastern stellar envelope shows velocities ranging from  $-100$  to  $+100 \text{ km s}^{-1}$  with a maximum value of  $+280 \text{ km s}^{-1}$

at about  $7''.0$  NE and  $17''.0$  SE of the nucleus, representing the absolute maximum of the entire velocity field. In summary, the gas in these regions presents the largest velocity deviations measured in the extended ionized regions of Arp 220 with a peak-to-peak value of  $600 \text{ km s}^{-1}$  at distances of about 5 to 7.5 kpc from the nucleus.

## 4. DISCUSSION

### 4.1. Origin of the Plumes: Starburst-driven Galactic Wind Structures?

Starburst-driven galactic winds, understood as generated by the collective effects of supernovae explosions and massive star winds generated in a (circum-)nuclear starburst, are able to compress and sweep the ambient interstellar medium of spiral galaxies with velocities of a few hundred  $\text{km s}^{-1}$  along the direction of the maximum pressure gradient, i.e. in a direction (almost) orthogonal to the disk of the galaxy (Heckman, Armus & Miley 1990 and references therein). Evidence for such winds have been reported in a number of edge-on spirals (Veilleux et al. 1994, Lehnert & Heckman 1996; Lehnert, Heckman & Weaver 1999; Strickland et al. 2002) where the finite thickness of the disk of the galaxy and the central location of the starburst (or AGN) defines the direction of the maximum pressure gradient, and therefore of the wind. As already pointed out by McDowell and collaborators (McD03), it is however very unlikely that the ordered interstellar medium and well defined geometry of spirals would exist in advanced mergers such as Arp 220. As already shown in the previous sections, the large scale gas/dust and stellar distribution do show in Arp 220 a complex structure characterized by a central dust lane, a low surface brightness stellar envelope and broad tidal tails at distances of several kpc. In addition, the large scale two-dimensional velocity field does not show any regular pattern with a privileged orientation or spin axis. All these characteristics support the idea that even if a galactic wind is generated in the central region (i.e. inner kpc) as a consequence of a (circum-)nuclear starburst, changes in the velocity structure and physical conditions of the interstellar medium in which the wind expands will disrupt it in an efficient way. With all these caveats in mind, the consistency of the starburst-driven wind scenario with the observed morphology and measured energetics of the plumes is evaluated in the following paragraphs.

Previous high spatial resolution integral field spectroscopy of the nuclear region did detect the presence of three different kinematical components consistent with rotating gas in a circumnuclear disk plus a tilted, outflowing gas (ACC01). The SE and NW plumes are oriented roughly along the same direction as the outflowing circumnuclear gas, and with an orientation similar to that of the spin axis of the circumnuclear rotating gas suggesting

that the plumes of ionized gas could be due to a galactic wind generated by the nuclear starburst. However, the plumes detected in Arp 220 show properties very different from the wind-generated structures detected in edge-on spirals with central starbursts or AGNs (see Table 2 for a summary of the different properties). The morphology of the ionized gas outside the plane of the galaxy in these nearby edge-on spirals indicates that the gas is concentrated in filaments (NGC 3079), sheets/filaments (M82), hollow shells (NGC 253), or biconical surfaces (NGC 2992). These structures indicate that the gas being ionized is mostly located in the surface of a bubble-like or cone-like structure, some with wide opening angles ( $\geq 90$  degrees) as in M82, NGC 2992 or NGC 3079, or some others with a more focussed beam ( $\sim 25$  degrees) like in NGC 253. The Arp 220 plumes show on the contrary a centrally concentrated optical, and X-ray (McD03), emission with, at the present resolution of about 1 kpc, no evidence of being resolved. This puts an upper limit of about 15 to 20 degrees for the opening angle if a cone-like or bubble-like structure as detected in nearby spirals is assumed. Therefore, if the plumes in Arp 220 were a consequence of a starburst-driven wind, the outflow channel would have to be very narrow, even narrower than the structure detected in NGC 253. Under the wind scenario, a narrow plume indicates a well collimated outflow. In order to produce this structure, the wind would have to have a lateral expansion velocity much smaller than the outflowing velocity, and the axis of the maximum pressure gradient would have to be very stable over distances of at least few kpcs. Integral field spectroscopy with higher spatial resolution ( $0''.5$ ) is needed in order to be able to resolve the plumes and investigate the velocity field across the plume.

Under the galactic wind scenario, the shocks generated by the expanding wind produce an  $H\alpha$  luminosity that is directly proportional to the preshock ambient density, and to the total surface of the hollow cone or bubble, and has a strong dependence ( $\propto V_s^{2.4}$ ) on the velocity of the shock (see for instance Veilleux, Shopbell & Miller 2001). Moreover, the total kinetic energy liberated by the starburst-driven wind is a few percent of the energy liberated by supernova explosions and massive stars winds, and therefore is directly proportional to the star formation rate (SFR in  $M_\odot \text{ yr}^{-1}$ ) as given by the expression  $E_k = 9.4 \times 10^{54} \times \text{SFR}$  ergs, if a continuous star formation over a period of 20 million years is assumed (Colina, L  pari & Macchetto 1991). According to this, since Arp 220 is an ultraluminous infrared galaxy, about 50 times more luminous than the nearby spirals where wind-related structures are detected, the total mass and kinetic energy of the ionized gas in the plumes is expected to be 50 times that measured in spirals. However, this is not the case. The observed maximum velocity (not corrected for projection effects) is relatively low for large kpc scale galactic winds, and the ionized gas mass is in the range measured in nearby galaxies (see Table 2). Moreover, if normalized by the infrared luminosity, the plumes in Arp 220 (and even the plumes with the additional contribution from the lobes)

are underluminous in X-ray and  $H\alpha$  emission by factors of at least 10 with respect to galaxies with prototype large scale, wind-induced structures including M82, NGC 2992 and NGC 3079 (see Table 2; see also Table 9 in Strickland et al. 2003). Only the small (overall extend of 1.3 kpc) shell detected in NGC 253 has an  $H\alpha$  to infrared luminosity ratio similar to those measured in the plumes and lobes of Arp 220.

In summary, the Arp 220’s plumes as traced by the optical emission lines and X-ray emission, are underluminous when compared with the galactic wind structures in nearby spirals. Therefore, if the starburst-driven wind scenario holds for Arp 220 plumes, the derived energetics indicates that the starburst-driven wind is much less efficient, by factors of at least 10 than in spirals with well developed wind-induced structures. Whether or not this behaviour is due to the existence in ULIRGs of an ambient dense interstellar medium with a complex three-dimensional structure and with a velocity field characterized by not having a privileged kinematical axis, requires further investigations and detailed modeling.

#### 4.2. Origin of the Lobes: Tidal-induced Structures?

Although the starburst-driven wind interpretation could still hold as an explanation for the origin of the ionized gas detected in the circumnuclear regions (ACC01) and even in the plumes, the large scale, i.e. several kpc size, two-dimensional kinematical structure presented here (see §3.4) does not support this scenario as the origin of the edge-brightened lobes detected in X-rays and  $H\alpha$ . As already mentioned (§3.4) the steepest gradients in the velocity field of the diffuse, extended gas are associated with substructures identified in the stellar light distribution, in particular with the southwestern side of the central dust lane, with the eastern extended stellar envelope, and with the broad, western tidal tail.

Therefore, the three-dimensional gas and stellar structure of a merger galaxy such as Arp 220 makes it difficult to assume a stable axis for the direction of the maximum pressure gradient that, as in edge-on spiral galaxies, would channel the gas from the central regions into the outer envelopes of the galaxy at distances of 10 kpc, or larger.

In the following we explore the scenario of the lobes as a merger by-product in Arp 220. As already pointed out by McDowell and collaborators (McD03), the different surface brightness and orientation of the plumes and lobes suggest that these two regions are dynamically distinct and points to a different origin. Within the framework of the merger scenario, the morphology of the X-ray/ $H\alpha$  lobes, with their edge-brightened structure and orientation, is best fitted by the off-center, face-on collision of two co-rotating disks with an impact velocity of less than a couple of hundred  $\text{km s}^{-1}$  (McD03). According to the specific dynamical simulation of the Arp 220 merger (see McD03 for detailed explanations), the

plumes and lobes are density condensations produced about 150 million years after closest approach and 15 million years after the formation of the dense central region. Following this model further, the edge-brightened  $H\alpha$  lobes are expanding outwards while also experiencing a general rotation, remnant of the original rotation of the two disks. The combination of the radial expanding flow and residual rotation of the disks is such that the line-of-sight velocity along each of the lobe rims ranges from  $+185$  to  $+25$   $\text{km s}^{-1}$  (E lobe) and  $-175$  to  $-20$   $\text{km s}^{-1}$  (W lobe) in the frame of the galaxy (McD03). The data do not have enough S/N to measure accurate velocities for each position along each of the rims, but are good enough to measure an average velocity for both E and W lobes. The measured velocities corresponding to  $+8 \pm 79$   $\text{km s}^{-1}$  for the E lobe and  $-79 \pm 58$   $\text{km s}^{-1}$  for the W lobe, are to first order in agreement with the predictions but a more detailed comparison with the models is needed. Since the lobes traced by the optical emission lines have a low surface brightness, low spatial resolution integral field spectroscopy with 10m class telescopes is required in order to obtain a significant improvement in the quality of the present spectra.

## 5. SUMMARY

The complex two-dimensional structure, ionization state and velocity field of the warm ionized gas in the ultraluminous infrared galaxy Arp 220 has been investigated for the first time over a region of about  $75''.0 \times 40''.0$  (i.e.  $28 \times 15$  kpc) using deep integral field optical spectroscopy with the INTEGRAL system. Arp 220 is the nearest ULIRG, and therefore the complexity of its extended structure reaching the low surface brightness levels of the ionized gas lobes previously detected in this unique target, has been investigated with unprecedented detail. The main results from this study are:

(a) The structure of the ionized gas presents three distinct regions at different linear scales that show, as already known, an overall morphology similar to that of the X-ray emitting gas. The three different regions are: (a) the circumnuclear region up to a radius of about  $5''.0$  (2 kpc) already studied in ACC01, (b) the elongated high surface brightness plume at radii between  $5''.0$  and  $10''.0$  (2 to 4 kpc), and (c) the extended low surface brightness lobes at radii between  $10''.0$  and  $35''.0$  (4 to 15 kpc).

(b) If the high surface brightness plumes are the result of a starburst-driven galactic wind, the measured energetics traced by the  $H\alpha$  and X-ray luminosities indicates that it must be at least one order of magnitude less efficient than the bubble-like or cone-like galactic wind structures detected in nearby edge-on galaxies. Also, the opening angle of the plume in Arp 220 is very narrow ( $\sim 20$  degrees) when compared with the wide opening angles

typical of wind generated structures. These non-standard properties could be caused by the complex three dimensional structure and kinematics of the gas and stellar components in advanced, luminous mergers such as Arp 220 that is very different from the ordered galactic structure of edge-on spirals, where a rotation disk with a finite thickness defines the axis of the outflowing wind, i.e. axis of maximum pressure gradient. This deserves proper investigations with detailed modeling and additional 2D spectroscopy.

(c) The kinematics of the lobes with average velocities of  $+8 \pm 79 \text{ km s}^{-1}$  and  $-79 \pm 58 \text{ km s}^{-1}$  for the E and W lobe, respectively, are to first order in agreement with the predictions of the tidal-induced scenario proposed by McDowell and collaborators (McD03) by which the gas condensations in the lobes are products of the merger that are animated by a combination of continuing expansion and residual rotation from the original rotation of the two disks involved in the merger. This scenario has to be explored further by measuring the two dimensional velocity structure of the gas along the rims of the lobes with better signal-to-noise spectra. Low spatial resolution integral field spectrographs mounted on 10m class telescopes would be needed for this purpose.

(d) The 2D velocity field shows its largest gradients ( $50 \text{ km s}^{-1} \text{ kpc}^{-1}$ ) and deviations ( $+280 \text{ km s}^{-1}$  to  $-320 \text{ km s}^{-1}$ ) from the systemic velocity in the low surface brightness ionized gas associated with the dust lane, the southeastern stellar envelope and the northwestern broad stellar tidal tail at distances of up to 7.5 kpc from the nucleus. Therefore, the velocity field of the gas at distances of a few to several kpc from the nucleus and with peak-to-peak deviations of  $600 \text{ km s}^{-1}$ , is associated with well defined stellar structures induced by the merger, i.e. is dominated by tidal-induced flows, and has no connection with a central starburst-driven galactic wind.

Additional results are:

(1) The ionized gaseous plume is elongated along PA 120 (SE) to PA320 (NW) with the southeastern side brighter than the northwestern side by a factor 4. An asymmetry on the radiation field as seen by the gas in the plumes is the most likely explanation for this difference. Alternative explanations like differences in the gas density and/or absorption effects through the plane of the galaxy are not supported by the present data.

(2) The [NII] and  $\text{H}\alpha$  emission peaks are separated by about 1 kpc in both sides of the plume. The ionization structure is such that the [NII] emission is closer to the nucleus and the  $\text{H}\alpha$  emission peaks at the tip of the plumes. The ionization state is consistent with it being produced by high velocity shocks expanding in a neutral ambient medium.

(3) The change in the ionization state along the plumes, in particular the NW plume, traced by a change in the [NII]/ $\text{H}\alpha$  ratio is interpreted as being produced by discontinuities



in the velocity field and/or density of the gas at the interface of the main stellar body of the galaxy with the low surface brightness extended envelope.

(4) The NW plume has a fainter, secondary component that runs almost parallel to the main component and south of it. The inner part of this secondary plume is also dominated by the [NII] emission while the outer region emits in  $H\alpha$ . This change in the [NII]/ $H\alpha$  ratio is interpreted, as before, as produced by variations in the velocity field and/or density of the ambient gas.

(5) The lobes show the same structure in both [NII] and  $H\alpha$  with their peak emissions spatially coincident, within the present resolution. However, contrary to the brightness distribution of the gas in the plumes, here the W lobe has a surface brightness higher than the southeastern lobe by a factor 3, as previously detected in x-rays.

Luis Colina thanks the Instituto de Astrofísica de Canarias and the Space Telescope Science Institute for their hospitality and financial support. We also thank Luis Cuesta by his help using GRAFICOS. Support for this work was provided by CICYT (Comisión Interministerial de Ciencia y Tecnología) through grants PB98-0340-C01, PB98-0340-C02 and AYA2002-01055. Dave Clements acknowledges funding by PPARC. Email exchanges and discussions with Dr. Strickland are also acknowledged.

Table 1. Properties of the Extended Ionized Regions in Arp 220

Region <sup>a</sup>	Distance <sup>b</sup> (kpc)	PA <sup>a</sup>	Extent (kpc × kpc)	$F_{obs}(\text{H}\alpha)^c$ ( $10^{-15}$ erg s $^{-1}$ cm $^{-2}$ )	$\log L(\text{H}\alpha)^d$ (erg s $^{-1}$ )	$M_{\text{H}\alpha}^e$ ( $10^4 M_{\odot}$ )	$V_{average}^f$ (km s $^{-1}$ )	$E_k^g$ ( $10^{49}$ erg)
Circumnuclear	0	–	$1.1 \times 1.1$	31.0	40.4	84.6	$5397 \pm 74$	–
NW_Plume_H $\alpha$	3.5	320	$1.5 \times 1.9$	1.9	39.1	4.4	$5305 \pm 39$	4
NW_Plume_[NII]	2.6	320	$1.3 \times 1.3$	1.0	38.8	2.4	$5291 \pm 21$	3
SE_Plume_H $\alpha$	3.5	125	$2.4 \times 2.4$	5.4	39.6	14.6	$5404 \pm 58$	–
SE_Plume_[NII]	2.0	125	$2.3 \times 2.3$	4.5	39.5	12.3	$5389 \pm 61$	–
W_Lobe	7.0	260	$7.1 \times 7.5$	9.3	39.8	21.5	$5321 \pm 54$	14
E_Lobe	10.1	114	$8.3 \times 5.6$	2.1	39.2	5.4	$5408 \pm 76$	–

<sup>a</sup>Regions labeled as NW\_Plume\_H $\alpha$  and NW\_Plume\_[NII] are the regions identified in the NW plume with the H $\alpha$  and [NII] emission peaks, respectively. The same applies for regions SE\_Plume\_H $\alpha$  and SE\_Plume\_[NII]

<sup>b</sup>Distances for the plumes are given as the distance between the nucleus and the local H $\alpha$  and [NII] peak emission in the plumes. For the lobes is the distance between the nucleus and the midpoint of the structure traced by the [NII] emission. The nucleus is identified here as the central bright source, even if this does not correspond with the true dust-enshrouded nucleus of the galaxy, not visible in the optical.

<sup>c</sup>Flux in units of  $10^{-15}$  erg s $^{-1}$  cm $^{-2}$  Å $^{-1}$ . Uncertainties of 10%–15%.

<sup>d</sup>Luminosity not corrected by internal extinction.

<sup>e</sup>Mass of ionized gas assuming an average density of 100 cm $^{-3}$ .

<sup>f</sup>The systemic velocity is  $5400 \pm 20$  km s $^{-1}$  from previous INTEGRAL measurements(ACC01). Velocities as measured and not corrected for projection effects.

<sup>g</sup>Kinetic energy assuming the mass and average velocity given in previous two columns and a systemic velocity of 5400 km s $^{-1}$ .

Table 2. Extended Ionized Gas: Arp 220 versus Galactic Winds in Spirals

Galaxy	Distance <sup>a</sup> (Mpc)	$\log L_{IR}$ <sup>b</sup> ( $L_{\odot}$ )	$L_{H\alpha}/L_{IR}$ <sup>c</sup> ( $10^{-5}$ )	$L_X/L_{IR}$ <sup>d</sup> ( $10^{-5}$ )	Extent <sup>e</sup> (kpc)	$M_{H\alpha}$ <sup>f</sup> ( $10^4 M_{\odot}$ )	$V_{max}$ <sup>g</sup> ( $\text{km s}^{-1}$ )	Structure <sup>h</sup>	$\theta$ <sup>ii</sup> (Degrees)	References <sup>j</sup>
Arp 220 Plumes	77.6	12.16	0.14	0.6	7	34	110	jet	15-20	1, 2
Arp 220 Lobes	77.6	12.16	0.16	0.3	24	27	160	hollow shell	70	1, 2
M82	3.0	10.52	16	2.5	2.4	66	300	filaments	90	3, 4
NGC 253	3.0	10.46	0.37	1.5	1.3	1	<100	hollow shell	20-26	3, 4, 5
NGC 2992	31	10.46	2740	-	5.6	$10^3$	200	biconical	125-135	6
NGC 3079	16	10.49	2.7	6.2	3	10	2000	filaments	90	3, 4, 7, 9

<sup>a</sup>Distances as given in reference (3) for M82, NGC 253 and NGC 3079, and in reference (6) for NGC 2992.

<sup>b</sup>Luminosities as given in reference (3) for M82, NGC 253 and NGC 3079, and in reference (6) for NGC 2992.

<sup>c</sup> $H\alpha$  luminosities corrected for internal reddening except for Arp 220 where the observed values given in Table 1 are used.

<sup>d</sup> $L_X$  indicates the soft X-ray luminosity of the extended, diffuse halo X-ray structure as given in reference (2) for Arp 220 and reference (4) for M82, NGC 253, and NGC 3079 and scaled to the distances assumed in column (2)

<sup>e</sup>End-to-end size of the bubble or cone shaped structure, not corrected for projection effects.

<sup>f</sup>Mass of the ionized gas assuming an average density of  $100 \text{ cm}^{-3}$ .

<sup>g</sup>Line of sight velocities given (in absolute values) relative to the velocity of the system.

<sup>h</sup>Structure defined from ground-based  $H\alpha$  imaging and/or high-resolution X-ray imaging.

<sup>i</sup>Opening angle of the structures as given in the references, or derived from the published images (M82)

<sup>j</sup>(1) this work; (2) McDowell et al. (2003); (3) Heckman et al. (1990); (4) Strickland et al. (2003); (5) Strickland et al. (2000); (6) Veilleux, Shopbell & Miller (2001); (7) Veilleux et al. (1994); (9) Cecil, Bland-Hawthorn & Veilleux (2002)

Fig. 1.— Archival WFPC2 I-band image of Arp 220 showing the central regions as well as the extended, low-surface brightness envelope. The overlays indicate the area covered by the three independent pointings with INTEGRAL. North is up and East is left.

Fig. 2.— Spatial distribution of the spectra around the redshifted  $H\alpha + [NII]$  spectral region obtained after the data reduction process is completed, including internal cross-calibration of the three pointings using the spectra on the overlapping regions.

Fig. 3.— INTEGRAL image of the stellar light distribution in the central regions and faint extended envelope of Arp 220 as traced by a line-free, narrow-red continuum window (7425–7455 Å) generated using all SB3 spectra. Although with a poorer resolution, note that the overall structure is similar to that detected in the higher resolution HST image (Figure 1). The contours are in arbitrary units and represent the 5%, 7%, 12%, 18%, 26%, 36%, 45%, 53%, 72%, 92% of the innermost contour. As in figure 1, North is up and East is left.

Fig. 4.— INTEGRAL images of the ionized gas distribution as traced by the  $H\alpha$  (a) and  $[NII]$  6583Å lines (b), respectively. The three different regions identified in X-rays, bright circumnuclear region, elongated plumes, and extended, diffuse lobes, are easily identified here. Changes in the ionization structure of the plumes, traced by the offsets between the  $H\alpha$  and  $[NII]$  emission peaks, are clearly visible. The contours for  $H\alpha$  represent surface brightness levels of 0.1%, 0.8%, 1.9%, 3.8%, 6.9%, 12.1%, 20.8%, 35.4%, 59.6%, and 100% of the maximum level ( $6.8 \times 10^{-16}$  erg cm $^{-2}$  s $^{-1}$  arcsec $^{-2}$ ). The orientation is the same as in previous figures.

Fig. 5.— Velocity field of the extended ionized gas obtained from the bright  $[NII]$  6583Å emission line. The different figures represent the correspondance of the velocity structures with the stellar,  $[NII]$ , and  $H\alpha$  light distributions, represented by contours in figures (a), (b) and (c), respectively.

## REFERENCES

- Arp, H., 1966, ApJS 14, 1
- Arribas, S., et al. 1998 SPIE, 3355, 821
- Arribas, S., & Colina, L. 2002, ApJ 573, 576
- Arribas, S., Colina, L., & Clements, D. 2001, ApJ 560, 160 (ACC01)
- Arribas, S., Mediavilla, E. 2000 in 'Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-wavelength Imaging Devices', Ed. W. van Breugel and J. Bland-Hawthorn, ASP, Conf. Ser., vol. 195, 295.
- Arribas, S., Mediavilla, E., García-Lorenzo, B. & del Burgo, C. 1997, ApJ 490, 227
- Baan, W.A., & Haschick, A.D. 1995, ApJ 454, 745
- Bingham, R.G., Gellatly, D.W., Jenkins, C.R., & Worswick, S.P. 1994 SPIE, 2198, 56
- Carico, D.P., Graham, J.R., Matthews, K., Wilson, T.D., Soifer, B.T., Neugebauer, G., & Sanders, D.B. 1990, ApJ 349, L39
- Cecil, G., Bland-Hawthorn, J., Veilleux, S., & Filippenko, A. 2001, ApJ 555, 338
- Clements, D.L., et al. 2002, ApJ 581, 974
- Colina, L., Lípári, S., & Macchetto, F. 1991, ApJ 379, 113
- Graham, J.R., Carico, D.P., Matthews, K., Neugebauer, G., Soifer, B.T., & Wilson, T.D., 1990, ApJ 349, L39
- Heckman, T. M., Armus, L., & Miley, G.K. 1990, ApJ Suppl. 74, 833
- Heckman, T.M., Dahlem, M., Eales, S.A., Fabbiano, G., & Weaver, K. 1996, ApJ 457, 616
- Hibbard, J.E., Vacca, W.A., & Yun, M.S. 2000, AJ 119, 1130
- Lehnert, M.D., & Heckman, T.M. 1996, ApJ 462, 651
- Lehnert, M.D., Heckman, T.M., & Weaver, K.A. 1999, ApJ 523, 575
- McDowell, J.C., et al. 2003, ApJ 591, 154 (McD03)
- Sakamoto, K., Scoville, N.Z., Yun, M.S., Crosas, M., Genzel, R., & Tacconi, L.J. 2000, ApJ 514, 68

- Scoville, N.Z., Yun, M.S., & Bryant, P. 1997, ApJ 484, 702
- Scoville, N.Z., Evans, A.S., Dinshaw, N., Thompson, R., Rieke, M., Schneider, G., Low, F.J., Hines, D., Stobie, B., Becklin, E., & Epps, H. 1998, ApJ 492, L107
- Scoville, N.Z. et al. 2000, AJ, 119, 991
- Soifer, B.T., Neugebauer, G., Matthews, K., Egami, E., Becklin, E.E., Weinberger, A.J., Ressler, M., Werner, M.W., Evans, A.S., Scoville, N.Z., Surace, J.A., & Condon, J.J. 2000, ApJ 509, 523
- Strickland, D.K. et al. 2002, ApJ 568, 689
- Strickland, D.K. et al. 2003, astro-ph/0306592
- Surace, J.A., Sanders, D.B., & Evans, A.S. 2000, ApJ 529, 170
- Veilleux, S. et al. 1994, ApJ 433, 48
- Veilleux, S., Shopbell, P.L., & Miller, S.T. 2001, ApJ 121, 198